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25 February 1980

USSR Report

ELECTRONICS AND ELECTRICAL ENGINEERING

(FOUO 4/80)

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POSSIBLE EXCITATION MECHANISMS OF IONOSPHERIC WAVE DUCTS

Moscow GEOMAGNETISM I AERONOMIYA in Russian Vol 19, No 5, Sep 79
pp 0769-0789

[Article by Yu. A. Kravtsov, M. V. Tinin and Yu. N. Cherkashin]

[Text] Introduction. The successful mastery of long-range radio communications and an increase in its reliability depends to a significant degree upon an understanding of the propagation of HF radio waves in the ionosphere. In recent years important progress has been achieved in this direction both in theory, where research on propagation of ionospheric wave ducts has undergone intensive development, and also in experimental methods of systematically studying long-range propagation.* Despite the successes achieved, a completely satisfactory theory of long-range HF radio wave propagation has yet to be worked out. The primary difficulty in creating such a theory, in our opinion, consists of the fact that, in order to explain the observed peculiarities of long-range propagation, it is necessary to call upon not one, but many radio wave transmission mechanisms** at once, and, in particular, many mechanisms of feeding the ionospheric wave ducts [134].

Under these conditions it is expedient to attempt to separate the influences of various factors--both in the theoretical and experimental plans. At present, such a separation has not been realized as a result of the limited potential of experimental equipment, as well as some blank spaces in the theory. This present article is directed toward qualitatively describing the possible feeding mechanisms of ionospheric wave ducts and thereby stimulating the organization of special radiophysical experiments for revealing the contribution of the separate factors to the observed effects and also stimulating the development of a corresponding theory.

The article was written on the basis of material presented in [6]. A substantially expanded text of the report with a detailed review of the literature was published in [7].

* The basic theoretical and experimental results of investigations in recent times are put forth in [1].

** H. A. Hess also directed attention to this [2]; various mechanisms of long-range propagation are also discussed in works [3-5].

§1. Mechanisms of Long-Range Propagation

a) Propagation in a surface waveguide (skip propagation). The simplest explanation of long-range propagation consists of an assumption made about the usual propagation of HF waves in an earth ionispheric waveguide; that is, within the surface waveguide (the Earth's surface forms one of the walls of such a waveguide).

The propagation of waves in the surface waveguide can be described by various methods. In the case of a stratified ionosphere any field within this waveguide can be represented either in the form of the sum of the normal waves dispersed along the waveguide or in the form of dispersion along the plane waves which are reflected from the Earth and the ionosphere in succession [3, 8-15]. In the latter case they sometimes speak of a number of skips. Within the HF wave boundary both types of field representations develop into an approximation of geometric optics. Taking into account the intricacy of dealing with a great many normal waves in the HF range, below we will rely basically upon a ray approximation which quite adequately describes the most important phenomena that arise during HF radio wave propagation in the ionosphere and, in particular, are convenient to use when calculating the horizontal heterogeneity of the ionosphere.

Skip propagation of radio waves explains a great number of experimentally observable phenomena, especially when there are few skips. However, when propagation is long-range, starting from about 5,000 to 7,000 km, the skip hypothesis is far from satisfactory. First of all, the calculated reduction in a round-the-world signal obtained by both A. N. Kazantsev's [16] and the NBS methods [17] as a rule exceeds the value of 5 dB, observed with multiple round-the-world signals (KS's). The estimated values of the field on other extended routes [5, 18-20] turn out to be low in comparison with the experiment. Furthermore, the maximal frequency at which round-the-world and return signals (OS's) are observed quite frequently exceeds (sometimes by twice!) the maximum usable frequency (MPCh) of the surface waveguide [4,5, 19-21]. Similar discrepencies are especially characteristic of an echo of the second type, the route of which passes through a subdued portion of the ionosphere, where the concentration of electrons is reduced. Finally, the direct measurements of the KS angles of entry in the vertical plane give values reaching 10-12° [22, 23] which do not keep to the skip-propagation hypothesis.

Such contradictions force one to assume the presence of other methods of propagation which differ from skip propagation.

b) Slip (anti-waveguide) propagation. As early as the 1930's O. Schmidt [24] considered it possible to explain long-range ionospheric propagation by the appearance of a lateral wave in the ionosphere, which itself is propagated along the abrupt boundary of the ionosphere. At present the hypothesis about the propagation of lateral waves along the abrupt boundary of the ionosphere is only of historical interest, since the real ionosphere has a smooth contour (this was emphasized by P. E. Krasnushkin as far back as 1947 [3]).

In the layer possessing the minimum dielectric permeability (that is, maximum concentration), the "successor" to the lateral wave hypothesis is the slip, or Pedersen, mechanism of propagation, in which one of the rays asymptotically approaches the apex of the smooth contour N(z) and the neighboring rays, running along at first very close to one another, gradually "fall off" the apex [25, 26] (fig. 1). In the vicinity of the apex of contour N(z) the rays behave as direct opposites of rays in a waveguide, so the method under examination is still called anti-waveguide [9].

In the vicinity of the maximum ray the attenuation of radio waves is less than in the lower layers of the ionosphere that are responsible for attenuating skip-propagated radio waves. However, the strong divergence of rays leads to an exponential decrease in field amplitude with respect to distance [8, 27-30] which essentially limits the distance at slip propagation. The range of the skip mechanism also decreases due to the sensitivity of Pedersen rays to incidental excitation: even a slight excitation can take the rays out of the anti-waveguide (attention was paid to this in work [31]).

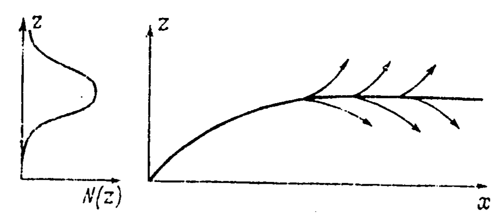

Fig. 1

At the same time, the depression of the apex of the contour N(z) contributes, as shown in works [28, 32, 33], to the retention of the rays. The fact is not ruled out that precisely through the depression of the contour N(z) one may explain the frequently observed propagation by means of Pedersen rays at a considerable distance, exceeding at times 5,000-6,000 km.

On the whole, the slip mechanism cannot lay claim to an independent explanation of the basic mechanisms of radio wave propagation at great distances, in comparison with the Earth's diameter, but, obviously, it can play an important role in the driving of ionospheric waveguides.

c) Propagation in ionospheric wave ducts. Using the altitude of maximum ionization distribution $z_{F\ max}$, which is small in comparison with the Earth's radius R, it is convenient to model the properties of the spherical ionosphere on a plane ionosphere with modified permeability [1, 9]:

$$\varepsilon_{\text{мод}}(z)=(1+2z/R)\,\varepsilon(z).$$

In fig. 2b is represented a typical function $\varepsilon_{\text{mod}}(z)$ for the contour of the electron concentration shown in fig. 2a. In fig. 2c curves are shown which reflect the behavior of waves in a phase plane $(z, P_z = dz/d\tau)$. These curves comply with the equation

$$\frac{dP_z}{dz}=\frac{1}{2P_{z\,\text{мод}}}\frac{d\varepsilon_{\text{мод}}}{dz},$$

which allows the integral

$$P_{z\,\text{мод}}^{2}-\varepsilon_{\text{мод}}(z)=\text{const}.$$

Not a single ray may get into the region in fig. 2c cross-hatched with vertical lines. The unruled area corresponds to the skip propagation in the surface waveguide: a portion of the waves turn down, not having reached the maximum layer E, while other rays transverse layer E and are reflected only by layer F.

Point A in fig. 2c marks the region of slip rays which are concentrated in the vicinity of the maximum layer E. Sooner or later these rays leave the apex at layer E, having gone down to the Earth or having risen to layer F. If layer F is transparent for the vertically falling radio wave, then on the phase plane (z, P_z) one more saddle point will appear in response to the rays slipping along the maximum layer F.

The rays which fall into the obliquely cross-hatched region do not come into contact with the Earth's surface (z=0) and correspond to the propagation in ionospheric wave ducts (IVK's). The lower region corresponds to the substratum wave duct (more precisely, the substratum E-duct). The behavior of the rays in the ionospheric wave duct is analogous to the whispering-gallery phenomenon: the rays ricochet along the lower edge of the stratum, not touching the Earth (in connection with this they sometimes speak of ricochet trajectories). In the case of a plane-stratified ionosphere ($R\to\infty$) the substratum duct disappears.

The upper region with oblique cross-hatching in fig. 2c corresponds to the interstrata IVK (the interstrata EF-duct). Unlike the substratum duct, the interstrata duct does not disappear as $R\to\infty$, that is, upon terminal transition to a plane-stratified ionosphere.

Generally speaking, fig 2c does not reflect the diversity of all possible IVK's. Thus, the stratification of region F may lead to the appearance of additional interstrata waveguides (F_1F_2 - duct), while the disappearance of the E-layer or an increase in the operating frequency can convert the interstrata EF-duct into a substratum F-duct.

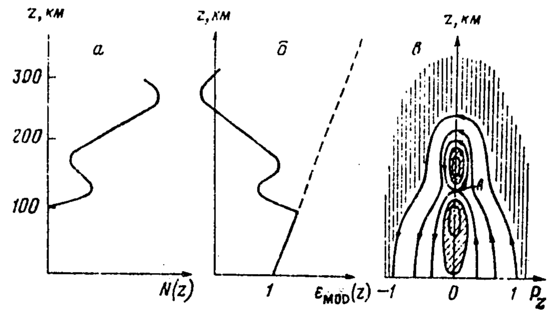

Fig. 2

Obviously, the first man to direct attention to the feasibility of explaining the round-the-world signals by means of propagation in the interstata waveguide was Hess [34], while P. E. Krasnushkin [3, 35] pointed out the possibility of long-range propagation in the substratum F-waveguide. The peculiarities of the waveguide mechanism--slight attenuation, the possibility of propagation at frequencies exceeding the surface maximum usable frequency and also the stability of the time delay--drew great attention from researchers [4, 18, 20, 26, 36-52].

If the substatum wave duct is located at altitudes of 70-80 km, the waves within it usually experience strong absorbtion in the D-layer. The interstrata EF- and substrata F-waveguides may be located in the 110-140 km interval, that is, approximately where the work of the Nv electron concentration on the frequency interference is minimal [39, 53]. Consequently, the absorbtion in these waveguides, as a role, is slight in comparison with the absorbtion in a surface waveguide. Along with this is connected a search for factors which, if only partially, "toss" radio waves into the ionospheric waveguides.

Numerical computations of the rays in the IVK have been carried out in works [54-60], and in works [61-65] investigations have been conducted into the position of the IVK axes and also the conditions for the existence and dissipation of waveguides with variations in the contour N(z). On the whole, the calculated values of the MPCh for the wave guide propagation mechanism agree with those observed experimentally. The adiabatic invariant method, proposed by A. V. Gurevich [39], was a new stage in the theory of long-range radio wave propagation in ionospheric wave ducts. This method, which was developed in the ensuing works [66-79], employs the horizontal gradients in the ionosphere a bit, and does not suppose a detailed enumeration of the ray trajectories in the IVK's as was done in the previous works. The simplification of the problem owing to this allows one to make an inference about the possibility of an IVK existing on a planetwide scale and to effectively describe the refraction capture of rays in the IVK. In conjunction with the global model of the terrestrial ionosphere it makes it possible to construct a map of the ducts in a selected frequency range (an expanded statement of the method is given in work [1]).

With the aid of the adiabatic invariant method in works [1, 66-79] conditions have been established for the existence of regular ionospheric ducts--E- amd F- substratum ducts and EF- interstrata ducts. It has been shown that there exists a latitudinal-longitudinal region of the ionosphere sufficient in extent to permit the propagation of waves in the IVK at frequencies that considerably exceed the maximum usable frequency in layer F1 (on the day-side of the Earth--up to 50 MHz). If the emitter and the receiver are located on the Earth, then the capture of radio wave energy in the interstrata EF-duct, a duct characterized by minimum absorbtion, is most effectively derived in the middle latitudes during daytime. The width of the spectrum of captured frequencies comprises 5-7 to 20 MHz. The spectrum of the capture angles reaches several degrees and decreases with frequency.

Thus, the adiabatic invariant method created a new basis for the analysis of existence conditions, the calculation of characteristics and the forecasting of long-range radio communications. The results obtained with this method agree well with the experimental data. However, with the surface distribution of the correspondents it is necessary to suppose the existence of some mechanisms for the induction of radio wave energy into the IVK in the vicinity of the emitter and its consequent drop to the Earth far from the transmitter. The most powerful capture mechanism is the tossing off of rays into the IVK owing to horizontal gradients in the electron concentration. This mechanism has also been examined in the majority of works.

Aside from the capture of rays in the IVK by the horizontal gradients, several mechanisms by now have been suggested for IVK feeding, chief among which is the dissipation of radio waves by small-scale heterogeneities in the electron concentration. It is possible that under some concrete conditions or others one of the assumed mechanisms prevails, whereas under other conditions further propagation is dependent upon several simultaneously operating factors. Up until now there has not been unanimity among researchers in the evaluation of the actual contribution of the various factors to the observed effects. It is precisely for this reason that we considered it expedient to provide concise comparative characteristics of the basic means of IVK feeding, broken down into two groups: refraction (§2) and diffraction (§3). We have also examined separately the feasibility of artificially influencing the ionosphere with the aim of IVK feeding (§4).

§2. Refraction Mechanisms for Capturing Waves in the Ionospheric Wave Guides

a) The action of strong horizontal gradients in the electron concentrations. Refraction saturation of the wave guides is possible in sections where there are horizontal gradients of the electron concentration, to begin with, on the day-night boundary, where the maximum value of the gradients of the critical frequency $\partial f_{KR}/\partial x$ reaches ~0.5 MHz/100 km [80, 81]. It is essential that there are also noticeable latitudinal gradients besides the longitudinal gradients, which are dependent upon the rising and setting of the sun.

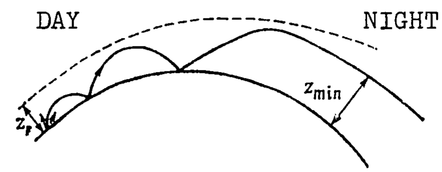

Fig. 3

P. E. Kransnushkin [3] explained the excitation of the substratum wave guide on the night-side of the route by a wave which comes from the day side and is reflected from the sloping transition region. Not yet having returned to Earth, the ray travels along a ricochet trajectory (fig. 3, in which the dotted line z_F depicts the location of the maximum electron concentration in region F and z_{min} is the minimum distance of the ricocheting ray from the Earth's surface). Substratum propagation on the night side with the subsequent drop into the twilight zone and surface propagation in the daylight zone are examined also in work [36].

Obviously, in order to feed the substratum F-waveguide it is essential that there be horizontal gradients in the upper portion of the trajectory which lie below the maximum in the F-layer, whereas for feeding the interstrata waveguide horizontal gradients in the region of maximum in the E-layer are also important. In order that the surface trajectory ends up being "locked" in the interstrata waveguide, the trajectory must encounter a much higher concentration of electrons when it drops down through the layer then when it is on the rise (fig. 4, where the curved dotted line 1 depicts a ray in a horizontally homogeneous ionosphere, while curve 2 is a ray caught in an interstrata waveguide; 3 is an isoline of the electron concentration N=const). Such a situation comes about in the twilight zone with the propagation of a surface wave from the night side.

b) Numerical calculations of the beam trajectory. It is convenient to characterize the horizontal gradients in the ionosphere by a change in three rough parameters of the ionosphere: the concentration at the maximum N_{max} and the width of layer H. A sufficiently extensive model of a single-layered, horizontally heterogeneous ionosphere supposes a simultaneous change of the three parameters indicated above

$$N(x, y, z) = N_{max}(x, y) f\left[\frac{z - z_{max}(x, y)}{H(x, y)}\right],$$

where $f(\xi)$ is the model function characterizing the shape of the vertical contour of the ionosphere. Calculations for the capture of beams for such a model have been performed, in particular, in the assumption in work [82] which says that the lower boundary of the ionosphere is fixed and only the value $N_{max}(x)$ changes. Numerical calculations of the capture and exit of beams in the interstrata and substratum waveguides have also been done in works [54, 56, 58-60, 83].

A model of the horizontal gradients can be made using a displacement of the center of the symmetrically spherical ionosphere relative to the Earth's center [84]. With the aid of such an eccentric model having a quasi-parabolic contour of the electron concentration, the sector of the angles is determined in which it is possible for the surface (slip) beams to shift over to ricochet trajectories (under certain conditions this sector comprises 0-6°). The width of the illuminated zone on the Earth can also be found, and the delay KS calculated

c) The adiabatic theory of ray capture. Even with all their merits, the numerical methods yield to the analytical ones in regard to the fact that they do not allow one to compose a general qualitative picture of the change in structure of the beams with variations in the ionospheric parameters. As far as the analytic methods of calculating the refraction capture of rays in the IVK are concerned, they are all approximations and utilize little of the horizontal gradients.

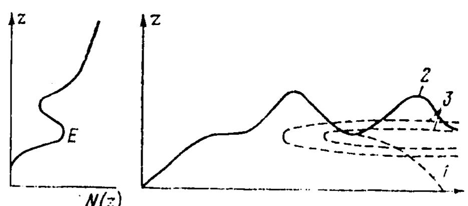

Fig. 4

An effective method of determining conditions for ray capture in the IVK is provided by the adiabatic invariant method [1, 39]. In accordance with [1], the adiabatic invariant for a ray in a gradually heterogeneous duct is written in the form:

$$I = \int_{\underline{z}}^{\bar{z}} \sqrt{\varepsilon_{\text{мод}}(z, x, y) - \tau_{\text{мод}}(\bar{z}, x, y)}\, dz,$$

where $\underline{z}$ and $\bar{z}$ are the lower and upper points of the ray's turn. The conditions for retaining the ray in the substratum waveguide boil down to the requirement $\underline{z}>0$, at which point the ray still has not touched the Earth. This is equivalent to the requirement

$$I < I_{\text{full}}(x, y) = \int_0^h \sqrt{\varepsilon_{\text{mno}}(z, x, y) - 1}\, dz,$$

where I_{full} is the so-called full volume of the substratum duct, and the altitude $h = h(x,y)$ is determined by the condition $\epsilon(h, s, y)=1$. A very similar condition can be written for the interstrata duct [1].

d) Non-adiabatic effects when rays are captured in the IVK. The horizontal gradients of the critical frequency, reaching 0.5 MHz/100 km in the twilight zone, make the characteristic horizontal scale (4000-5000 km) equal to the oscillation period of the ricochet trajectory. Under these conditions the stability of the adiabatic invariant I is disrupted and the necessity of plotting the ray trajectories themselves arises. This relates especially to conditions close to slip propagation when the ray's spacing is great and very small gradients lead to a disruption in the applicability of the adiabatic approximation (for example, in work[23], 20% variations in the adaibatic invariant were found. The variations were computed using known values of $\underline{z}$ and $\bar{z}$ from the trajectory calculations).

In essence, the method of the adiabatic invariant, containing no information about the "phase" of the trajectory, allows one to foresee only the possibility of capture and adiabatic propagation of the ray in the given duct [71]. The question is whether the given trajectory falls within the given duct and it demands a detailed study of the rays on the basis of this or that method: with the aid of the resolution of the trajectory by two parameters [87], with the aid of an averaging method [88] or even the numerical methods [89].

One of the effects connected with the disruption of adiabatic invariance--the oscillating ray effect--has been pointed out in work [90] purely on the basis of rays plotted along the example of work [91] (in the latter, waves were studied in an irregular metallic waveguide). In accordance with [90], after a beam of rays passes through an irregular section of the IVK a periodic oscillation of the rays arises, accompanied by an alteration in the width of the duct, which is not described by the adiabatic approximation. If the E-layer separating the interstrata EF-waveguide from the surface portion is sufficiently thin, then the rays can "spill out" of the IVK under the action of the oscillating rays. Thus, departures from adiabaticity may serve as the cause of an escape of energy from the heterogeneous section of the interstrata EF-duct. According to the theorem of reciprocity it is possible, obviously, to feed the surface wave's waveguide through the place where the rays are "leaking" out of the irregular section. This makes it possible to speak of the existence of a non-adiabatic mechanism for feeding the IVK like a multiform refraction mechanism.

On the whole, numerical and analytical calculations have shown that strong horizontal gradients can deflect rays by several degrees, and, thus, the refraction feeding of the IVK possesses high efficiency. With a narrow diagram for the emitter (also on the order of several degrees) a very considerable (up to 10-20%) share of the radiated energy can get into the IVK. It is precisely for this reason that the IVK refraction feeding mechanism is freely employed in various theoretical constructs.

The strong horizontal gradients of the electron concentration, however, are not recorded often enough in order to explain the majority of instances of observed radio signals on long-range paths. To this must be added the fact that the horizontal gradients alone are hardly capable of insuring the feed to the IVK as well as the release of radiation to a receiver several thousands of kilometers away.

As a result, it is necessary to seek out less effective, but then again more regular, mechanisms of the IVK feed which are able to excite the IVK independently or in conjunction with weak or moderate horizontal gradients.

Below we will examine several such less-effective mechanisms.

e) Refraction on large-scale ionospheric heterogeneities. Aside from strong horizontal gradients of electron concentration with dimensions of 1000 km and more arising, for example, in the twilight zone, there also exist great heterogeneities with dimensions of up to 100-500 km. Pertaining to such heterogeneities are, first of all, large-scale migrating perturbations dependent upon gravitational waves in the ionosphere and also sporadic formations of type E_s. Although the large-scale heterogeneities are characterized by smaller horizontal gradients than those that exist in the twilight zone, it may in a number of cases excite the IVK independently. More probable, however, is the feeding of IVK's by large-scale heterogeneities against a background of moderate horizontal gradients.

The refractive index in the ionosphere depends not only on the electron concentration N but also the geomagnetic field H and the collision frequency ν [92]. On the whole, the influence of the horizontal gradient of these values is less than the influence of the horizontal gradient N, but in the direction of the twilight line in which N changes comparitively little (at equinox the twilight line is directed exactly along the meridian) the role of the gradients H and ν can turn out to be decisive, since the magnetic field changes most strongly right along the meridian.

Values of the complementary vertical angle θ at which the ray can be deflected under the action of gradients H and ν have been cited in works [93, 94]. It has turned out that the angle of incidence θ changes by a fraction of a degree due to a change in the magnetic field, but by hundreds of fractions of a degree due to a change in ν.

f) Refraction on localized heterogeneities. Aside from the large-scale heterogeneities with dimensions of 100 km and more, there are also smaller localized heterogeneities in the ionosphere, a meeting with which can also bring about the entrapment of a beam of rays in the IVK.

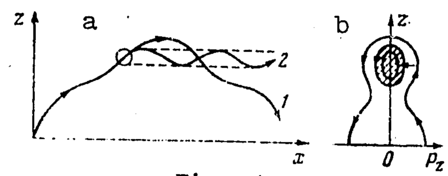

Fig. 5

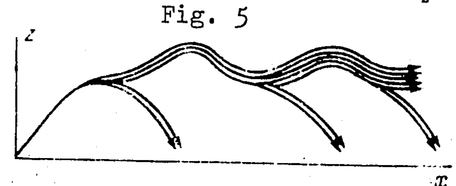

Fig. 6

One can qualitatively describe the capture of rays in the IVK under the action of a localized heterogeneity as an acute change in the angle of incidence θ of the ray and, consequently, of the value $P_z = \sqrt{\epsilon}\cos\theta$. The acute transition of the ray from the surface trajectory 1 to the waveguide trajectory 2 is shown in fig. 5a, while the corresponding skip on the phase plane (z, P_z) is shown in fig. 5b.

The change in the ray's trajectory can be calculated using the perturbation method [31]. Such calculations were undertaken in work [95] in which, in particular, the intersection of the capture and the heterogeneity has been computed, that is, the portion of the cross-sectional area that insures the turn of the rays into the IVK. For the $\Delta\gamma$ sector of the departure angles from the source, corresponding to the captured rays, the value $\Delta\gamma = 4 \cdot 10^{-3}$ rad has been obtained. The calculations have been carried out for a Gaussian heterogeneity with a 10 km radius with a deflection of the refractive index from the regular ionosphere $\delta n = 10^{-2}$ (it is considered that the heterogeneity is dispersed between the E- and F-layers).

g) Diffusion of rays on a random heterogeneous ionosphere. In the presence in the ionosphere of a great number of randomly dispersed, comparitively small heterogeneities* it is natural to resort to statistical methods to describe rays in the ionosphere. In work [95], for example, the averaging of the capture cross-section in various locations of heterogeneities of identical shapes has been carried out.

* Of course, these small heterogeneities should be large in comparison with the Fresnel zone, that is. Their dimensions should exceed approximately several kilometers. The dimensional spectrum of heterogeneitics in the ionosphere was studied in many works, for example, in [96].

In works [97, 98] the diffusion approximation has been examined for the rays. The approximation describes the refraction of waves on random heterogeneities and takes into account, unlike the Born approximation, the processes of multiple dispersion. Although this approximation is adopted only for small deflection of the ray's angle of inclination away from the unperturbed direction [99], it is entirely suitable for research into the capture of energy in the IVK as a result of a random displacement of the rays. Previously, a diffusion equation was already used in work [100, 101] for analyzing the statistics of rays in the plane-stratified ionosphere with the continuous contour N(z) when waveguide propagation is impossible. In works [97, 98] the sphericity of the Earth and the feasibility of forming ducts has been taken into account.

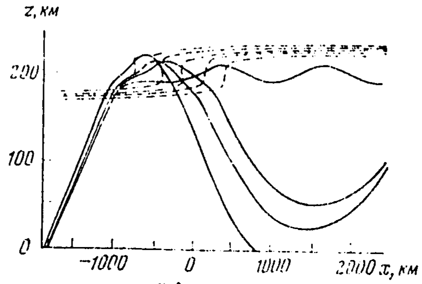

Fig. 7

Qualitatively speaking, the picture of IVK feeding owing to ray refraction on random heterogeneities takes the following form. A portion of the energy from the initial beam can be caught in the IVK on the first skip. Farther along, a part of the captured energy passes over to the "deep" trajectories approaching the IVK axis, and other parts leave the IVK on the second and subsequent skips. The processes taking place here are depicted schematically in fig. 6 for the case of an interstrata IVK in a plane-stratified ionosphere (the branching of the lines is a conventional characteristic of ray diffusion).

One may think that ray refraction on random heterogeneities is no less significant a factor in IVK excitation than the one-time dispersion on small-scale heterogeneities (see below).

h) The role of slip propagation in feeding the IVK. Slip rays are very susceptible to ionospheric heterogeneities: under the action of various perturbation factors (horizontal gradients of concentration, localized heterogeneities, random displacement, non-linear effects, etc.) such rays sooner or later leave the region of maximum ionization, at which point a portion of the rays may return to the Earth and the other portion may fall into the IVK. In exactly the same way, the captured rays, traveling at shallow angles in respect to the horizon, may leave the IVK by the action of slight perturbations and become slip rays. Then, by the action of this or that perturbation they may drop down to the Earth.

Thanks to this, the slip mechanism can play an important role in feeding the IVK and when drawing radiation out of the IVK--not independently, but in conjunction with this or that perturbation (horizontal gradients, random heterogeneities, etc.).

The considerations expressed here are confirmed by certain calculations and experiments. In work [83], with the aid of numerical modeling, the relative role of various rays in exciting the IVK has been studied, using the model of a horizontally heterogeneous ionosphere possessing two maximums of electron concentration (double-layered model). Fig. 7 depicts a system of rays in the case when the electron concentration at the layer's maximum decreases along the propagation path (isolines $\epsilon_{MOD}(z)$=const are shown in fig. 7 in dotted lines). It is evident in fig. 7 that the slip rays in the given case excite both the interstrata and substratum waveguides, while at the same time rays from a very narrow sector of the angles (fractions of a degree) get into the ionospheric wave ducts. In accordance with [83], the additional (in comparison with propagation in free space) reduction of the signal captured in these waveguides reaches 20-30 dB.

Despite these losses, the combination of the slip mechanism plus the IVK is able to compete with the skip propagation mechanism on long routes, since the losses upon excitation are compensated for by a decrease in attenuation of the high-traveling waves captured in the IVK. The efficiency of the slip mechanism of capture should grow with an increase in frequency. In the first place, at high frequencies the attenuation along the skip rays decreases and, in the second place, slip rays near the MPCh differ in the least degree from the waveguide rays, which facilitates their capture by the action of some perturbation factor.

The excitation of the interstrata waveguide by slip rays is possible not only during a decrease but also during an increase in the ionization in the lower layer [83], since it is necessary only to slightly change the rays' angle of pitch to effect their capture in the IVK. As was shown in works [102, 103], the presence nearby of the apex of a lower layer of weak undulating heterogeneities, with an amplitude of ~2% of the background ionization, also leads to the capture of slip rays in the IVK.

In work [104] it has been found with the aid of a hybrid method that the capture of slip rays in the substratum IKV can turn out to be sufficiently effective in the case of a unilayered ionosphere, too, if the height of the layer increases along the route. In this case the slip rays seem to follow the layer's maximum.

Furthermore, a comparison of the trajectory calculations with certain results of feedback observations on the Khabarovsk-Irkutsk route [23] has shown that the arrival angles in the vertical plane are difficult to explain without supposing the participation of a slip mechanism in feeding the IVK. Besides this, one can use the presence of the slip mechanism's input of energy into the IVK (or its withdrawal) to explain the frequency dependence of the vertical arrival angles of round-the-world signals [106] observed in works [23, 105].

§3. Diffraction Mechanisms of Feeding the IVK

a) Subbarrier leaking of the field through a wall of the waveguide. That portion of the energy that gets into the waveguide due to leakage (fig. 8, where U is the amplitude of the wave field) can be estimated (for a plane-incident wave) by a method of phase integrals:

$$\alpha(\theta_0)\approx\exp\left\{-2k\int_{z_1}^{z_2}\sqrt{|\epsilon(z)-\sin^2\theta_0|}dz\right\},$$

where z_1 and z_2 are the lower and upper boundaries of the barrier that satisfy the condition $\epsilon(z)=\epsilon(\overline{z})=\sin^2\theta_0$. Even for the slip angles of the drop ($\theta\to\pi/2$) the contribution of the captured energy is usually not large, since the thickness of the barrier usually exceeds to a considerable degree the length of the wave. For a non-planar wave the share of the captured energy is determined by an integral from $\alpha(\theta_0)$ with a diagram of the source's direction $f(\theta_0)$ as a weighting function. The energy which leaks into the waveguide gradually punches its way out due to the same tunneling effect as was schematically shown in fig. 8b in an IVK of type EF with $\epsilon(z)$, described in fig. 8a (fig. 8c showed the distribution of field U in a waveguide). A ray in the waveguide completes, roughly speaking, $\sim 1/\alpha$ skips before the captured ray's amplitude decreases e times.

The calculations carried out in work [107] for a spherically stratified ionosphere point out that only those waves which correspond to the narrow sector of the slip angles effectively seep into the interstrata IVK and that the relative magnitude of the energy captured in the IVK is $\sim 10^{-3}$ for the specific model of the ionosphere and for a radiation diagram $\sim 1°$ wide. Such an order of magnitude is also given by the numerical calculations of the field using the method of the parabolic equation [108, 109].

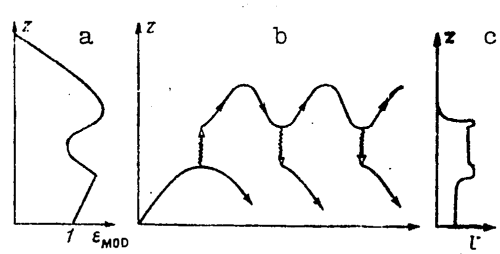

Fig. 8

On the whole, the tunnel effect is somewhat inferior in efficiency to the refraction mechanisms of energy capture in the IVK (a comparison of the tunnel effect with the other mechanisms using data from numerical calculations was done in work [109]).

b) Dispersion on small-scale random heterogeneities. There is in the ionosphere a regular presence of small-scale (smaller than the Fresnel zone) heterogeneities, on which rays may scatter and, thus, feed the IVK [4, 34]. This mechanism is examined in many works on the basis of the theory of one-time dispersion.

Work [110] assumes a semi-empirical dependence of the field upon distance when propagation is long-range. In this work the capture of energy in the IVK due to dispersion is examined. Work [111] establishes a satisfactory correspondence between the dispersion values achieved in a Born approximation and certain experimental data.

A detailed investigation of the role of dispersion was undertaken in [112, 113]. As was shown in [113], the optimal capture of one-time dispersed radio waves in the 10-20 MHz range comes about during conditions in which heterogeneities on the scale of $\sim$50-100 m are located near the axis of the wave duct. Greater heterogeneities on the scale of $\gtrsim$0.5-1 km may also contribute to feeding the waveguide, but only due to a one-time dispersion under the conditions of a strongly perturbed ionosphere, when the relative fluctuations of the electron concentration reach $5\cdot(10^{-2}\text{-}10^{-1})$ [112, 113]. Such a repeated dispersion is described by the diffusion approximation examined in [2]. The intermode transformation of normal waves within the waveguide owing to the action of comparitively large heterogeneities is described in [114].

Work [112] notes that an increased heterogeneity of the polar ionosphere during periods of magnetic perturbations can aid in the explanation of the observed connection between the frequency of appearance of feedback and the magnetic activity.

A computation of the elongation of the heterogeneities along the magnetic field was performed in works [112, 115, 116], and in work [117, 118] it was noted that the near-caustic region, where a "distension" effect in the field is observed [92], makes, on the whole, an insignificant contribution toward dispersion.

c) Polarization capture. This type of capture relates neither to the refraction nor to the diffraction mechanisms. We examine polarization capture in this paragraph just for the reason that we do not wish to provide a separate section for this little-effective mechanism.

Works [119-123] noted that, by virtue of the variety of refractive indices for the magneto-ionic components, the ionospheric waveguides for them will be varied. In particular, the lower wall separating the waveguide from the surface correspondent will be higher for an extraordinary wave in an interstrata waveguide than for an ordinary one. Thus, the ordinary wave, sent by a surface emitter at an angle approaching critical, can be transformed during intersection of the waveguide into an extraordinary wave which turns out to be already captured. The transformation comes about due to heterogeneities in the ionospheric plasma. The contribution of the captured energy is determined first of all by the orientation of the route with respect to the Earth's magnetic pole, as well as the magnitude of the transformation ratio. The values show, however, that this capture mechanism is extremely weak.

§4. Feeding the IVK With the Aid of Artificial Ionospheric Perturbations

a) Dispersion on small-scale heterogeneities which appear due to the action of powerful radio emissions. In recent times there has been an extreme intensification of interest in the behavior of the ionosphere due to the action of powerful radio waves emitted from the Earth [124-125]. Certain non-linear effects which appear in a strong electromagnetic field can be utilized to artificially feed radiation to or draw radiation out of the IVK.

One of the effects that appears in the ionosphere under the action of a powerful radio wave radiated from the surface consists of the appearance of small-scale heterogeneities that are greatly stretched along the magnetic pole [125]. Such heterogeneitics have cross-sectional dimensions comparable to the length of the radio wave and therefore can effectively toss energy into the IVK [116, 125, 126].

b) Creation of an artificial horizontal gradient of the electron concentration. This method was discussed in A. V. Gurevich's work [39], in which the role of non-linear defocusing of powerful radiation sent into the ionosphere from the Earth's surface was discussed. By the action of defocusing, the pitch angle of the peripheral rays in the radiated beam is altered, at which point the lower rays, under certain conditions, can be caught in the IVK. At the same time the captured energy may comprise a considerable portion of the energy of the descending ray: according to the data [39], it is up to 50-100% for the substratum duct and up to 5-20% in the case of an interstrata IVK.

c) A "burst" of powerful radiation in the IVK. If a sufficiently thin layer of plasma (for example, stratification in the F-region) is encountered along the route of a strong radio wave emitted from the Earth, then the radio wave may "break through" this layer [127]. Reflected from a more powerful overlying stratum, the wave will turn upwards, but its amplitude will be less than that of a descending wave (as a result of attenuation and divergence of the rays). Therefore, the weakened wave heading downward will bring about effects that are less non-linear and will be unable to break through the thin layer anew. As a result, the wave will appear to be locked into the interstrata waveguide. Evaluations of the efficiency of such an entrapment of rays in the IVK were given in work [128].

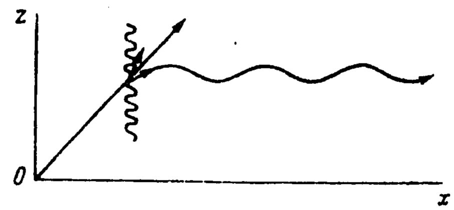

Fig. 9

d) Diffusion on a diffraction grating which appears owing to the action of a standing wave. It has been discovered experimentally that during irradiation of the ionosphere with a vertical beam a diffraction grating is formed as a result of the non-linear effects in the ionosphere. The diffraction grating reproduces the structure of a standing wave [129] (theoretical research on this effect was done also in [130, 131). This grating can effectively feed the IVK if the wave falls upon the grating at a certain angle (fig. 9). As it was shown in works [132, 133], upon scattering, even a weak, elongated, undulating perturbation at Briggs' angle may insure a sufficiently high transformation ratio for the falling wave into a captured wave. Calculations of the intensity of the captured wave are carried out analogous to the calculation of light diffraction in the ultrasonic.

§5. Combined Forms (Ducts) of Propagation

a) A multiplicity of propagation ducts. The transfer of energy over long distances in the HF band is possible not only by skip, waveguide or slip trajectories, but also by various combinations of these mechanisms of propagation. To this one must add the fact that radiation into the IVK can be accomplished by one of several of the methods examined above, while the extraction of radiation out of the IVK can be accomplished through one or another of the methods from the same set. Thus, there arise many methods of transferring radio wave energy over great distances or a multiplicity of propagation ducts. An example of such a duct is the source-skip ray-scattering-IVK-slip propagation-receiver chain.

In the real ionosphere there appears (although to a small degree) the action of all possible types of propagation, but the effective (prevailing) propagation duct will be only that one for which the transfer constant is maximal. According to the expression of L. M. Yerukhimov, the "principal of the least attenuation" is operating under such conditions and, in accordance with it, the wave "selects" the propagation duct in which attenuation is at a minimum. It stands to reason that the waves do not arrive at the observation point in one single form, but, if the radio signal is substantially stronger in one duct than in the others, it actually appears that there is no duct other than the resultant field.

Obviously, the possibility of wave propagation along many ducts has itself already determined important features of long-range propagation--in particular, the likelihood of long-range radio communications. Really, even if the likelihood of the appearance of separate, favorable (for the input and extraction of radiation into and out of the IVK) types of ionospheric perturbations is small, then in the presence of an IVK on a long route the likelihood of just one of the many favorable factors cropping up may appear to be considerably great. In accordance with this, chances also increase for long-range radio wave propagation. At the same time, the efficiency of energy transmission along one duct or another lies to a considerable degree in the hands of the experimenter.

From this point of view, setting up reliable radio communications between a pair of remote points means a search for such modes of emission and reception (first of all, selection of the time of broadcast, the frequency and the direction of emission) as will, with high probability, bring about a stable coupling of the favorable factors, that is, certain stable propagation ducts.

Certainly, the exposure of stable ducts, characteristic of the given route, season, etc., would be conducive to more reliable forecasting of long-range radio communications.

The basic difficulties in exposing all the possible and most probable propagation ducts are connected with the intricacy, and sometimes even ambiguity, of interpreting the experimental data, since even the modern techniques used in radiophysical experimentation (a branched radiosonde network, multi-frequency apparatus, directional antennas, probing with an IZS [further expansion not given]) still do not insure in many cases a sufficient solution of the possible propagation ducts. This is all the more important when comparing the efficiency of two or more ducts.

In our opinion, under these conditions considerably more attention than at present must be devoted to the separate investigations of the various mechanisms for the input and output of radiation to and from the IVK, which would make it possible to expose the relative roles of individual mechanisms according to their energy efficiency and expose their connections with latitudinal-longitudinal, diurnal, seasonal and other variables in the ionosphere.

At present one may, in connection with the role of these or those mechanisms, express more or less plausible hypotheses. The various natural mechanisms for feeding the IVK could be tentatively arranged in the following order in accordance with their possible roles: refraction in the presence of horizontal gradients in the electron concentration; refraction on large heterogeneities; scattering on small random heterogeneities; scattering (refraction) on large random heterogeneities; refraction on localized heterogeneities; non-adiabatic capture and extraction of the rays; and leaking across the barrier.

b) The problem of separating the propagation ducts. The difficulties in separating the propagation ducts into their component elements are great, although not insurmountable. Researchers working in many locations at present are concerned, first of all, with obtaining the most detailed information possible about the state of the ionosphere and the behavior of the wave field immediately along the propagation route. This means carrying out a certain combination of measures: arranging many ionosondes and intermediate receiving stations for controlling field potential along the route; modulating the radiation modes (frequency and duration of the signals, direction of emission in the vertical plane); and improving equipment at the receiving stations (aside from determining the delay time τ, special attention should be given to measuring the arrival angles and the statistical characteristics of the received signal).

Such measures are being taken by all the research groups (of course, only to the extent possible). They take into consideration the multiple character of propagation ducts when analyzing experimental data. However, they are far from doing this everywhere. Meanwhile, comparing the experimental data with well thought-out model computations of the field potentials for these or those propagation-duct models would help to narrow the number of competing hypotheses.

Of course, it is difficult to completely rig a long route with measuring apparatus; it is more expedient to conduct the investigation along two lines: 1) more detailed research on long routes with the available apparatus. 2) experiments on well-equipped but comparatively short routes (let us say, two-skip) in order to purposefully study the efficiency and frequency of appearance of these or those mechanisms of feeding energy to and extracting energy from of the IVK. The analysis of several such routes, located at various latitudes, would allow us to make long-range radio communication forecasts that are more reliable than those we have at present.

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